ON THE PROTON KLYSTRON

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Summary

This paper summarizes the key features of a new prospective application of the high-energy intense proton beams to exciting a linear accelerating structure which was recently proposed [1,2] and called the "proton klystron". This scheme opens up rather inexpensive way to ultra-high energies in a wide selection of charged-particle beams [2]. On the other hand such an addition to an existing big proton machine will considerably increase the capabilities of generating (and accelerating) various secondary particle beams [3].

Introduction

The energy stored in the proton beams has already reached a level of 3 MJ in the CERN SPS and in the FNAL Main Ring, while far higher energies and intensities are being projected. Due to small beam emittance and energy spread this stored energy is excellently adapted for conversion into the electromagnetic energy of excitation of a linear accelerating structure at a small wavelength, thus enabling a very high accelerating gradient.

A stored energy of 3 MJ suffices for exciting the 5 cm accelerating structure at a rate of acceleration of 100 MeV/m and total length 50 km. In the limit, this makes it possible to accelerate charged particles ($p,\bar{p},e^{\pm}, \mu^{\pm}, \pi^{\pm}$) to an energy of 5 TeV, while the energy of the basis accelerator beam can be far lower. In principle one can transfer up to half the energy stored in this beam to the particles being accelerated. However, in this limiting case the energy of accelerated particles will be substantially lower than the extreme value above quoted. The HF pumping power (even without longitudinal compression of the exciting proton beam) can reach 100 GW in modern accelerators; longitudinal compression allows one to increase this value sharply in addition. Note that employing superconducting magnet and RF systems in the basis proton machine can make the efficiency of converting the power from the mains into proton beam power relatively high.

The principle of the proton klystron

Now we shall treat the problem of the efficient transfer of the large stored energy in the proton beam to a linear accelerating structure i.e. to an appropriately selected diaphragmed waveguide of a simple design.

First of all a proton beam homogeneous in time should be converted into a density - modulated beam with the necessary wavelength (of the order of a centimeter). The modulation can be carried out by transmission of the beam through the accelerating section supplied at the needed wavelength, where the beam energy is modulated by the value considerably exceeding the energy spread of the primary proton beam (this spread in SPS is less than 50 MeV). The subsequent bunching is optimally performed in the bending modulator (fig. 1a) with an appropriate focusing.

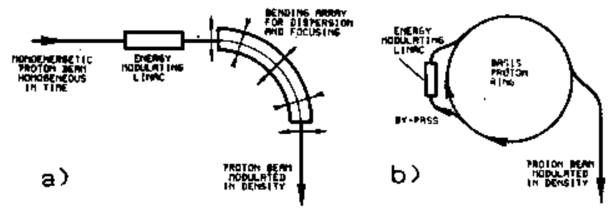

Fig. 1. Two versions of the bending modulator.

For needed harmonic of the current I_λ in the emerging beam be close to the maximum possible, i.e. $I_\lambda \approx 2I$, where I is the proton current before modulation, it is useful to add higher harmonics to the energy modulation or to employ cascade bunching. After this operation the proton beam is directed into the appropriate linear accelerating structure having the necessary magnetic quadrupole focusing to keep the protons within the apertures of the diaphragms of the waveguide (fig. 2).

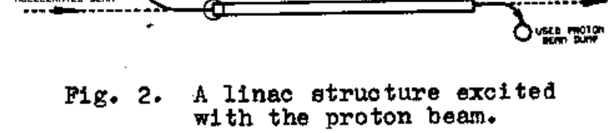

Fig. 2. A linac structure excited with the proton beam.

One can employ as the bending modulator either a special magnetic tract through which the ejected proton beam is passed or the ring of the basis proton accelerator. In the latter case a linac (of energy of the order of 100 MeV) can be set up in a by-pass adjacent to one of the machine straight sections (fig. 1b). After finishing the accelerating cycle the beam is directed for a single pass into this modulating linac while the required density modulation arises in the subsequent motion in the arcs.

Energy attainable in a linac with the proton klystron

Let us pass such a density-modulated beam of ultrarelativistic protons through a linear accelerating structure tuned to the wavelength λ corresponding to the first modulation harmonic. A high-frequency field will be excited in this structure that decelerates the protons, which will transfer their energy to the electromagnetic field. At first the amplitude E_0 of this field will increase in proportion to the total charge eN of the protons that have passed through the given cross-section:

$$E_0 \approx 100 \frac{Ne}{\lambda^2} \approx 1.5 \cdot 10^{-11} \frac{N}{\lambda^2_{cm}} \ (\mathrm{MV/cm}).$$

This increase will continue up to the decay time τ_d in the system, which is proportional to $\lambda^{3/2}$. For $\lambda = 1$ cm it amounts to about 20 ns in a copper waveguide. Yet if the time of passage of the proton current is much larger than τ_d, an amplitude of the electric field is established in the structure that is proportional to the mean proton current I:

$$E_0 = 2IR \approx 3 \frac{I_A}{\sqrt{\lambda_{cm}}} \ (\mathrm{MV/cm}).$$

In the latter formula R is the lineal impedance of the structure and I_A is the proton current in amperes. Here we have assumed that the electron loading arising from cold emission caused by the large excited electric field is still negligibly small.

If one directly employs the proton current of the contemporary record-setting high-energy accelerators, one can obtain in a structure having $\lambda = 1$ cm an established (within the time of revolution in these accelerators, which amounts to about 20 μs) field amplitude of about 0.6 MV/cm. Even a relatively small preliminary bunching of the proton beam will enable one to obtain an effective field up to 1.5 MV/cm in the accelerating structure, which is at the limit for the electric strength of the surface. The total time of existence of this field will be proportionally smaller than without this bunching. If one injects any type of ultrarelativistic particles into the accelerating phase (for the given sign of charge of the particles) along with the exciting proton beam, one can accelerate them at a rate of 60–150 GeV/km, respectively (fig. 2).

Thus one can accelerate particles up to an energy approaching the limiting energy of the basis accelerator. The limiting intensity of the accelerated beam will amount here to about 10% of the intensity of the basis accelerator (with a monochromaticity of the order of a percent).

Upon dividing the primary beam into several bunches of sufficient length and passing them separately (with the correct time shift) through consecutive linear accelerating structures (fig. 3), each of which brings about almost complete braking of the primary beam, one can make the particles

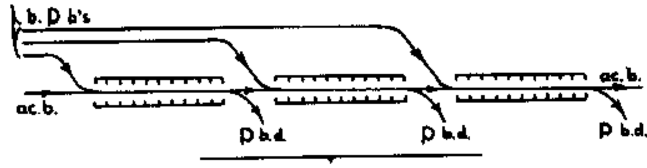

Fig. 3. Beam distributing for consecutive linac structures in many-fold energy step-up.

being accelerated pass successively through all the accelerating structures, while proportionally elevating the energy of the accelerated particles as compared with the energy of the basis accelerator. Naturally, the limiting intensity of the beam of accelerated particles will be proportionally lower (in average).

The needed redistribution in time of the individual parts of the exciting beam – the spent and the "fresh" bunches must arrive simultaneously at each new section – can be carried out with different schemes. Logically the simplest is to install in the tunnel of the main accelerator some additional pulsed magnetic small-aperture full-energy tracks having somewhat different revolution times for particles with a given momentum, and to admit each bunch, which occupies its corresponding fraction of the perimeter of the accelerator, into its own track (fig. 4a). When all the bunches coincide in azimuthal position one must, after

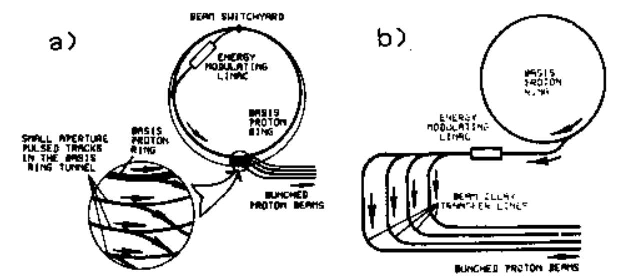

Fig. 4. Two versions of re-arranging the proton beam time structure required for the many-fold energy step-up.

the operation of short-wavelength modulation of the density of each of the bunches, release them and direct them toward the corresponding sections of the linear accelerating structure. This same operation can also be performed with long delays in transfer channels, although this requires additional tunnels (fig. 4b).

In order to confine the particles of both the exciting and the accelerated beams within the apertures in the diaphragmed waveguide of the linear accelerating structure, one requires sufficiently strong focusing. Here one must attain simultaneous stability of the transverse oscillations of particles with sharply differing momenta. Estimates show that the beams of modern proton accelerators will pass through almost without losses when one attains the optimal quadrupole focusing for accelerated particles having a momentum of several GeV/c, even for waveguides in the centimeter range. For the detailed analysis of the beam transmission which accounts for strong focusing, finite beam emittance and yields an optimal λ, see ref. 2.

Another problem involving the passage through the same structure of ultrarelativistic particles having sharply varying γ--factors, and hence somewhat differing velocities, is to effect the correct relative phasing of these particles. In order to remove the consequences of the gradual lag of the particles having lower velocity, after each section of length $\lambda\gamma^2_{min}/2$ one must separate the exciting beam and the beam being accelerated and retard one beam with respect to the other by about $3\lambda/4$ via a difference in the path lengths to the entrance to the next accelerating section. This method allows one simultaneously to rid the beam being accelerated of particles having different masses.

Prospects in high-energy physics with the proton klystron

Let us examine the potentialities of the variant of acceleration described. If the conditions given above are satisfied, the acceleration of stable charged particles (if their velocity is close enough to the speed of light at the outset) gives rise to no difficulties, independently of the type of particles. It is of interest both to increase the energy of protons (with injection of a fraction of the primary protons in the accelerating phase of the hf potential) and to accelerate preliminarily stored and cooled antiprotons and ions, or to accelerate electrons and positrons without the restrictions associated with the catastrophic growth of synchrotron radiation characteristic of circular accelerators (in linear acceleration the losses in noncoherent radiation are negligibly small). It is of especial interest to accelerate polarized particles of all types-since with linear acceleration the depolarizing effects can be made very small.

Accelerators based on proton klystrons can be of greatest interest for accelerating unstable particles. The required rate of acceleration $dE/dS|_0$ from the energy E_i to the energy E_f while the number of particles in the beam being accelerated is decreased by decay from N_i to N_f is given by the formula

$$\frac{dE}{dS}\bigg|_0 = \frac{mc}{\tau_0}\,\frac{\ln(E_f/E_i)}{\ln(N_i/N_f)} .$$

Here m and τ_0 are the mass and lifetime of the particles in the rest frame of reference.

For muons the quantity mc/τ_0 amounts to 1.6 keV/cm, and 0.18 MeV/cm for pions. We see directly from this that a linear accelerator with a rate of gain of energy of about 1 MeV/cm enables one to accelerate both muons and pions to the limiting energy with small intensity losses.

It is rational to cool a muon beam before acceleration by ionization cooling, and to bunch the muons into regions close to the maxima of the accelerating voltage with a bending modulator prior to injection. It is desirable to perform the needed bunching of pion beams to be injected into the superlinac by bunching the high-quality primary proton beam used for generating the pions.

For the acceleration of charged kaons an accelerating gradient greater than 3 MeV/cm is required. Apparently such gradients unavoidably cause a complete shunting of the structure by cold-emission electrons, and the only means to obtain such a field is that proposed in ref. 4 (reviewed in ref. 3), also based on the proton klystron concept.

The use of superlinacs with proton klystrons allows one in principle to perform many experiments with the colliding beams on the basis of existing superhigh-energy proton accelerators, or those under construction or in planning, if one can achieve the required luminosity.

In order to create $\pi^+\pi^-$ colliding beams, after one has accelerated the pions in a superlinac, one must inject them into a magnetic track with an extremely high value of the magnetic field (in order to increase the number of collisions per lifetime). In this case the limiting mean luminosity $L_\Sigma^{\pi\pi}$ will be

$$L_\Sigma^{\pi\pi} = \frac{\zeta \dot N_p}{\ell_t^{eff}}\,\frac{N_\pi}{\ell_\pi}\,\frac{p_\pi p}{(m_\pi c)^2}\,\frac{eH\tau_\pi}{2\pi m_\pi c} .$$

Here ζ is the efficiency of proton-pion conversion; $\dot N_p$ is the number of protons supplied by the basis accelerator per second; N_π is the number of pions in one superbunch; ℓ_t^{eff} is the effective length of the optimized conversion target; ℓ_π is the length of a pion superbunch in the magnetic track, and at the same time, the value of the beta-function at the collision point, p_π is the momentum of the pions after conversion, p is the momentum of the accelerated pions; H is the value of the magnetic field in the track where the collisions occur; and τ_π is the restframe lifetime of a pion.

If we assume that $\dot N_p = 10^{13}$ p/sec, $N_\pi = 10^{11}$, $\zeta = 10^{-1}$, $p_\pi = 5$ GeV/c, $p = 500$ GeV/c, H = 100 kG, $\ell_t^{eff} = 1$ cm, and $\ell_\pi = 1$ m, then we obtain the following limiting luminosity:

$$L_\Sigma^{\pi\pi} = 3\cdot 10^{27}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}.$$

In principle, this suffices for experiments to study the fundamental properties of the pion-pion strong interaction.

When one employs the same system for pion-proton experiments with substitution of protons for the positive pions, the limiting mean luminosity is

$$L_{\Sigma}^{\pi p} = L_{\Sigma}^{\pi\pi} \frac{N_p^1}{N_\pi}.$$

With a number of particles $N_p^1 = 10^{12}$ in one proton bunch and with the other parameters as before, this gives

$$L_{\Sigma}^{\pi p} = 3\cdot 10^{28}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}.$$

If we utilize the system being discussed to perform muon-muon experiments with colliding beams while using muon beams with ionization cooling (under the condition of keeping the normalized emittance of the muons at collision equal to their emittance immediately after the ultimate ionization cooling), then we obtain the following limiting mean luminosity):

$$L_{\Sigma}^{\mu\mu} = \frac{\zeta \dot{N}_p}{\ell_c} \frac{N_\mu}{\ell_\mu} \frac{p}{2m_e c} \frac{eH\tau_\mu}{2\pi m_\mu c}.$$

Here ℓ_c is the length of the ionization-cooling target, which is equal to the value of the beta-function of the cooling agent in the region of the target; m_e is the mass of an electron. Upon assuming that $\ell_c = 1$ cm and $\ell_\mu = 5$ cm, with the rest of the parameters as given above, we obtain an estimate for the limiting luminosity:

$$L_{\Sigma}^{\mu\mu} = 3\cdot 10^{31}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}.$$

Superlinacs excited by proton klystrons can be used also for performing experiments with electron-positron linear colliding beams. With the "standard" productivity of the proton accelerator of $\dot{N}_p = 10^{13}$ p/sec, the limiting electron-positron luminosity will be

$$L_{\Sigma}^{e^+e^-} = 10^{31}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}.$$

A luminosity at this level is already of interest; moreover, the productivity of synchrotrons is expected to increase even further.

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